

# THE NATURE OF DAMPED LYMAN- $\alpha$ AND MGII ABSORBERS EXPLORED WITH THEIR DUST CONTENTS

MASATAKA FUKUGITA<sup>1,2</sup> AND BRICE MÉNARD<sup>3,1,4</sup>

<sup>1</sup> Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo  
 Kashiwa 277-8583, Japan

<sup>2</sup> Institute for Advanced Study, Princeton, NJ 08540, USA and

<sup>3</sup> Department of Physics & Astronomy, Johns Hopkins University  
 3400 N. Charles Street, Baltimore, MD 21218, USA

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## ABSTRACT

We estimate the abundance of dust in damped Lyman- $\alpha$  absorbers (DLA) by statistically measuring the excess reddening they induce on their background quasars. We detect systematic reddening behind DLA consistent with the SMC type reddening curve, but it is inconsistent with the Milky Way type reddening. We find that metallicity derived from the dust abundance, on average, anticorrelates with the column density of neutral hydrogen,  $\langle Z \rangle \sim N_{\text{HI}}^{-1}$ , meaning that the column density of metals is constant irrespective of the column density of hydrogen. This indicates that the prime origin of metals seen in damped Lyman- $\alpha$  absorbers is not by *in situ* star formation, with which  $Z \sim N_{\text{HI}}^{+0.4}$  is expected from the empirical star formation law, contrary to our observation. We interpret the metals observed in absorbers being deposited dominantly from nearby galaxies by galactic winds ubiquitous in intergalactic space. We find that this metallicity H I column density relation for damped Lyman- $\alpha$  clouds extrapolates to Mg II clouds.

*Subject headings:* dust, extinction; galaxies:halos; quasars: absorption lines

## 1. INTRODUCTION

Whether intervening absorbers seen in quasar spectra are aggregates of primordial material or results of the activity in galaxies is an elementary problem. In a previous publication (Ménard & Fukugita 2012; hereinafter MF12) it was advocated that Mg II clouds are likely to be a product of the activity of nearby galaxies with gas exported by galactic winds. This inference is based on the fact that the observed dust abundance of Mg II clouds relative to gas takes a value typical of galactic disks, while the star formation activity is not observed nor expected in such clouds.

MF12 estimates that the global H I abundance in Mg II clouds is  $\Omega_{\text{HI}}(\text{MgII}) \approx 1.5 \times 10^{-4}$ , which is approximately 3% of the fuel consumed by star formation by the present epoch, or roughly 6% at  $z \approx 2$ . The amount of matter expelled through galactic winds in actively star forming galaxies is, when measured, in many cases nearly as much as the star formation rate (e.g., Heckman et al. 2009; Veilleux et al. 2005; Weiner et al. 2009). The fraction of H I in Mg II absorbers, which is 10 – 20 % of re-shed gas of stars as a whole, is not an unreasonable amount as a product resulting from the star formation activity in galaxies. It is also shown that dust in Mg II clouds accounts for half the amount of dust estimated to reside outside galaxies.

The analysis gives the example that the dust abundance, as explored by extinction of light rays passing through the absorbers, provides us with a useful indicator of the heavy element abundance, assuming that photometry is accurate. The estimate of the dust abundance, hence of metallicity, depends little on other astrophysical parameters, unlike estimates from spectroscopy. This

suggests that more could be learned from dust studies for other classes of absorbers.

The global mass density of H I in damped Lyman- $\alpha$  (DLA) clouds has been estimated to be  $\Omega_{\text{HI}}(\text{DLA}) \approx (4 - 10) \times 10^{-4}$  at  $z \approx 2$  by Prochaska & Wolfe (2009) using the quasar spectroscopic data of SDSS DR5, and more recently by Noterdaeme et al. (2012) using SDSS DR9. This quoted range arises from different treatments of the spectral continuum around the damped Lyman  $\alpha$  line. Whichever value is taken, the DLA mass density is significantly larger than the H I mass density in the Mg II absorbers, which is estimated to be  $\Omega_{\text{HI}}(\text{MgII}) \approx 1.5 \times 10^{-4}$  (MF12). Should DLA be a product of the stellar activity of galaxies, it requires  $\sim 50 - 100\%$  of re-shed materials at  $z \approx 2$ , where star formation has completed half its present amount, to produce DLA: the mass density of DLA increases towards higher redshift. At  $z \gtrsim 3$ , gas in DLA seems to require more material than the activity from stars produces. Hence they cannot be ascribed to star formation activity.

Studies of individual DLAs have indicated their metallicity  $[\text{Fe}/\text{H}] = -0.5$  to  $-2$  (e.g., Prochaska et al. 2003; Rafelski et al. 2012), an order of magnitude lower than that of galaxies. This contrasts to Mg II absorbers, which MF12 showed to have metallicity of the order of solar. These observations may be taken in favour of the interpretation that there would be two distinct populations of absorbers as to their origins: DLAs belong to one different from gas clouds hosting Mg II absorbers. This also induces the question as to where the metallicity of DLAs arises from.

There have been a few attempts to detect reddening of quasars behind DLAs (Vladilo et al. 2008; Frank & Péroux 2010; Khare et al. 2011). The results have not always led to positive detections. The difficulty is that

<sup>4</sup> Alfred P. Sloan Fellow

the reddening signal is small, of the order of a few hundredths of magnitude, whereas sample variation due to objects is an order of magnitude larger. For photometric studies, one needs to define accurately reference colours without absorbers. With spectroscopic work one needs accurate sensitivity calibrations over wide wavelengths.

In this paper we estimate the mean reddening effects induced by DLAs by comparing broad band flux of the quasar light showing Lyman  $\alpha$  absorptions with damped wings to that without absorbers. We use accurately calibrated SDSS broad band photometry, and yet we limit the redshift range of quasars to minimise the scatter of fiducial colours of quasars. We are concerned with a photometric accuracy smaller than 0.1 mag. It turns out that choosing the right range of quasar redshift, and also of absorber redshift, is important in keeping errors of colours small. Specifically, care must be made so that passbands are away from the Lyman edge or the Lyman  $\alpha$  line for absorbers.

When reddening is detected, we can estimate metallicity by assuming that 30% of heavy elements condense to dust grains, which corresponds to the case when all silicate and a substantial fraction of graphite (15–50%) condense into dust grains of astronomical silicate and graphite or hydrocarbon (e.g., Weingartner & Draine 2001). We study whether metallicity is correlated with the hydrogen column density of the cloud, and also examine if any difference is seen between Mg II absorbers and DLAs in the metallicity H I column density relation.

## 2. THE DATA

We use the quasar catalogue compiled by Pâris et al. (2012) based on the ninth data release of the Sloan Digital Sky Survey III (hereinafter DR9, Ahn et al. 2012). Noterdaeme et al. (2012) analyzed these 87822 quasars and identified 12081 clouds with the H I column density  $N_{\text{HI}} \geq 10^{20} \text{cm}^{-2}$  for redshift  $z \geq 1.9$ . The column density is estimated using Voigt profile fitting. About 57% of the clouds (6839) have  $N_{\text{HI}} \geq 10^{20.3} \text{cm}^{-2}$  with damped wings. The quasar sample in the SDSS catalogue consists of a union of quasars arisen from several different quasar selections. Since accurate photometry and accurate colour property are of our prime concern, we take its ‘uniform sample’ which is derived from the uniform colour selection. This uniform sample contains 23499 quasars. We further restrict the redshift range to  $2.3 < z < 3.1$ , after examining the variation of colours, to keep the photometric homogeneity of the selection (14024 quasars).

Zhu & Ménard (2012) identified in the DR9 uniform quasar sample 10877 Mg II absorbers with rest equivalent widths  $W_0 > 0.3 \text{ \AA}$ , of which 6635 have  $W_0 > 0.8 \text{ \AA}$ , in the redshift range  $z = 0.36$  and 2.5. We restrict our analysis to the Mg II absorbers with  $W_0 > 0.8 \text{ \AA}$ , below which the sample completeness drops to  $\lesssim 50\%$  (Nestor et al. 2005), although completeness is not important to our analysis.

The DLA and Mg II samples overlap in the redshift range  $1.9 \leq z \leq 2.5$ . We restrict primarily our analysis to the range  $2.1 \leq z_{\text{abs}} \leq 2.3$ , avoiding redshift tails of both DLA and Mg II absorber distributions. With this selection we can minimise the effect of Lyman opacities, which contributes to colours we choose. This overlap allows us to study the relation between the two popula-

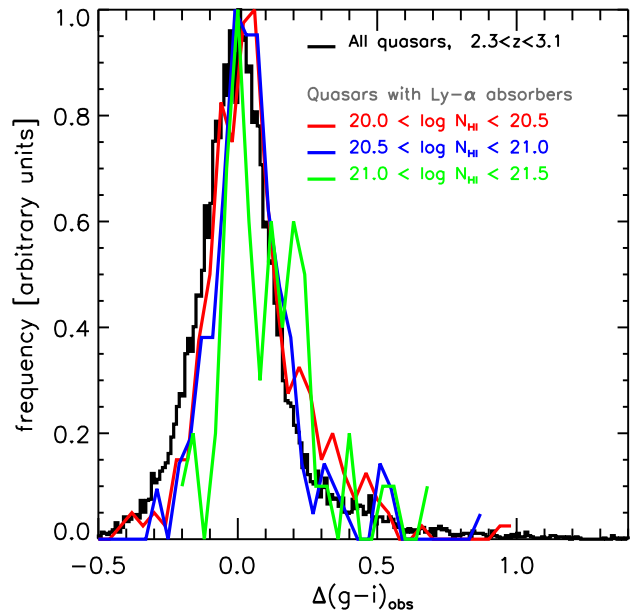


FIG. 1.— Distribution of colour excess  $\Delta(g-i)$  for quasars showing Lyman  $\alpha$  absorption for three bins of hydrogen column densities. The thin (black) histogram shows the distribution for the quasar sample with  $2.3 < z < 3.1$ .

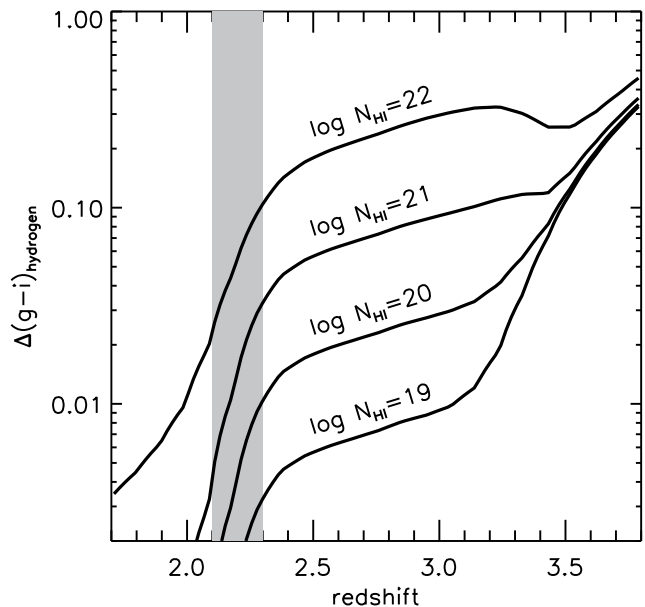


FIG. 2.— Expected colour excess  $\Delta(g-i)$  due to Lyman opacity in absorbers as a function of redshift for specified values of  $N_{\text{HI}}$ .

tions of absorbers. This redshift interval contains in the common quasar sample 1211 DLAs and 680 Mg II absorbers, and 150 among those are common in both samples. These statistics indicate that 12% of DLA show Mg II absorption lines detected with  $W_0 > 0.8 \text{ \AA}$ , and conversely 22% of Mg II absorbers are DLAs.

## 3. DUST REDDENING AND METALLICITY OF DLA

As was done for Mg II absorbers in MF12, we measure mean reddening of background quasars induced by

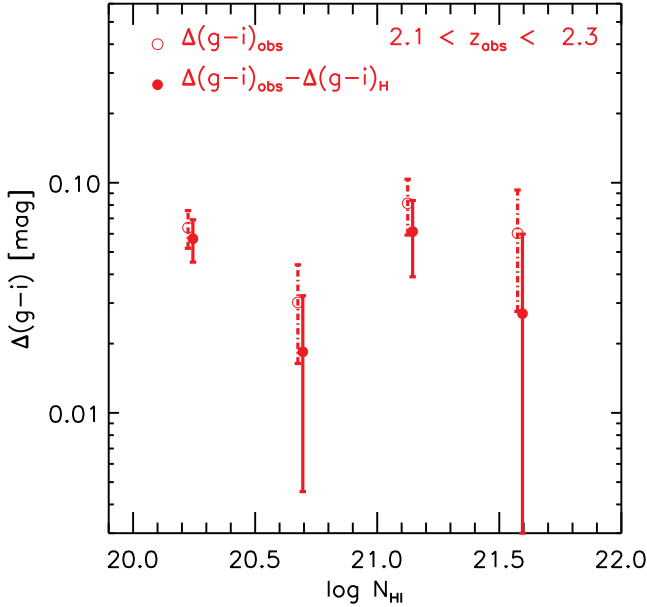


FIG. 3.— Colour excess  $\Delta(g-i)$  caused by Lyman opacities in absorbers with  $2.1 < z < 2.3$  as a function of  $N_{\text{HI}}$ . The open circles show the measured median and the filled circles show the values corrected for hydrogen opacity.

intervening clouds. We estimate the colour excess

$$\Delta(g-i)_{\text{obs}} = (g-i) - \langle (g-i) \rangle, \quad (1)$$

where the average is the median to avoid largely scattered data points that occasionally happen<sup>2</sup>, rather than the mean.

Since we want to detect very small value of reddening, it is of crucial importance to give reference colour of quasars accurately. We limit the redshift range of quasars to  $2.3 < z < 3.1$ , for which the scatter of measured quasar colour is substantially reduced. Using the difference between median and mean as a measure as to how regular is the distribution, we find that it is better to restrict quasars to the uniform sample, as noted above. It is also important to restrict the redshift range of quasars. We find that the difference of the two averages, when studied as a function of redshift, is smaller than 0.01 mag for  $z < 2.75$ . The inclusion of quasars  $2.75 < z < 3.1$  increases the resulting errors only a little. Dividing the quasar sample into a  $\delta z = 0.25$  bin, we set the median of  $g-i$  to zero at each bin. The other test is to compare colours of all quasars with those that do not show DLA signatures. Here, the effect of the reddening due to absorbers is diluted by the presence of a larger population that does not show DLA signatures by about 10 times. The difference is smaller than 0.02 mag. This test, which shows null detection below the noise level and the homogeneity of colour, serves to see what is the level

<sup>2</sup> In MF12 the reference quasar sample is constructed from quasars without showing absorption lines. In the present work this selection is removed, since it modifies the resulting reference colours only by  $< 3 \times 10^{-3}$ , which is much smaller than we are concerned with in our analysis. We remark that the average colour information as a function of redshift given in the DR9 quasar catalogue (Pâris et al. 2012) is made by taking a mode of the distribution. So their values show a substantial irregularity up to 0.05 mag against the mean or the median average.

of the signal we could detect: this reassures us that we can detect the change of colours if it is larger than 0.02 mag.

In Figure 1 we show the distributions of  $\Delta(g-i)$  for our quasars with and without hydrogen absorbers. The distributions with hydrogen absorbers for three bins of  $N_{\text{HI}}$  overlap with each other. When compared to the reference  $\Delta(g-i)$  distribution of quasars (thinner black curve), we see that those with Lyman absorption are shifted redwards by an amount of about 0.05 mag. The sample dispersion of  $\Delta(g-i)$  colour is 0.20 mag which indicates that one may detect a reddening signal, say, as small as 0.02 mag only when averaged over 100 or more absorbers. Each measurement, which sometimes gives negative values, does not tell about reddening for individual quasars. Their colour shift are 0.05 mag or even less, which is buried in much larger scatters, arising from both variation among individual quasars and measurement errors. Averaging over a large sample is needed to detect a meaningful reddening signal.

The colour excess is mainly caused by dust reddening and by hydrogen Lyman opacity. Figure 2 shows the expected reddening of  $g-i$  due to Lyman opacity as a function of redshift for specified values of  $N_{\text{HI}}$ . One sees the first rise due to the Lyman  $\alpha$  excitation and the second due to the Lyman edge. When the Lyman edge is met,  $\Delta(g-i)$  due to hydrogen ionisation is larger than that from dust, which is of the order of 0.05 mag (as we see in Figure 3 below).

Even away from the Lyman edge, reddening due to the Lyman excitation is nonnegligible. We must subtract it to find reddening due to dust. We note the advantage to work with  $z \leq 2.3$ , for which the effect of Lyman  $\alpha$  opacity is not yet very important: Lyman  $\alpha$  enters the  $g$  band above  $z = 2.3$ , which requires a large subtraction to obtain dust reddening.

Using the relation between  $E(B-V)$  and  $N_{\text{H}}$  for the Milky Way at the solar metallicity (Bohlin, Savage & Drake 1978) and the extinction curve, the reddening of  $\Delta(g-i)$  colour is translated into metallicity, via the abundance of dust, as

$$Z/Z_{\odot} = \frac{\langle \Delta(g-i)_{\text{obs}} - \Delta(g-i)_{\text{Ly}\alpha} \rangle}{0.30 \times 10^{-21} k(z_{\text{abs}}) N_{\text{H}}} \quad (2)$$

where  $N_{\text{H}}$  is the hydrogen column density,  $Z$  is metallicity, and  $k(z)$  is the ‘K-correction’ with the dust extinction curve for  $g-i$  colour. There are typically two types of extinction curves, Milky Way (MW) type and SMC type. It has been shown that dust in Mg II clouds obeys the SMC type extinction curve (e.g., York et al. 2006; Ménard et al. 2008; MF12). Which extinction curve works for DLAs is also a part of the task given to our study.

The most conspicuous difference between the Milky Way (MW) extinction curve and the SMC curve is the presence of a hump in the former at 2175Å. The K-correction for MW extinction wildly varies as a function of redshift for  $z > 0.8$  when the feature enters the  $g$  band till it goes away from the  $i$  passband for  $z > 2.8$ . The K correction becomes even negative for  $z = 2.2 - 2.5$ , which is close to the redshift of absorbers that concern

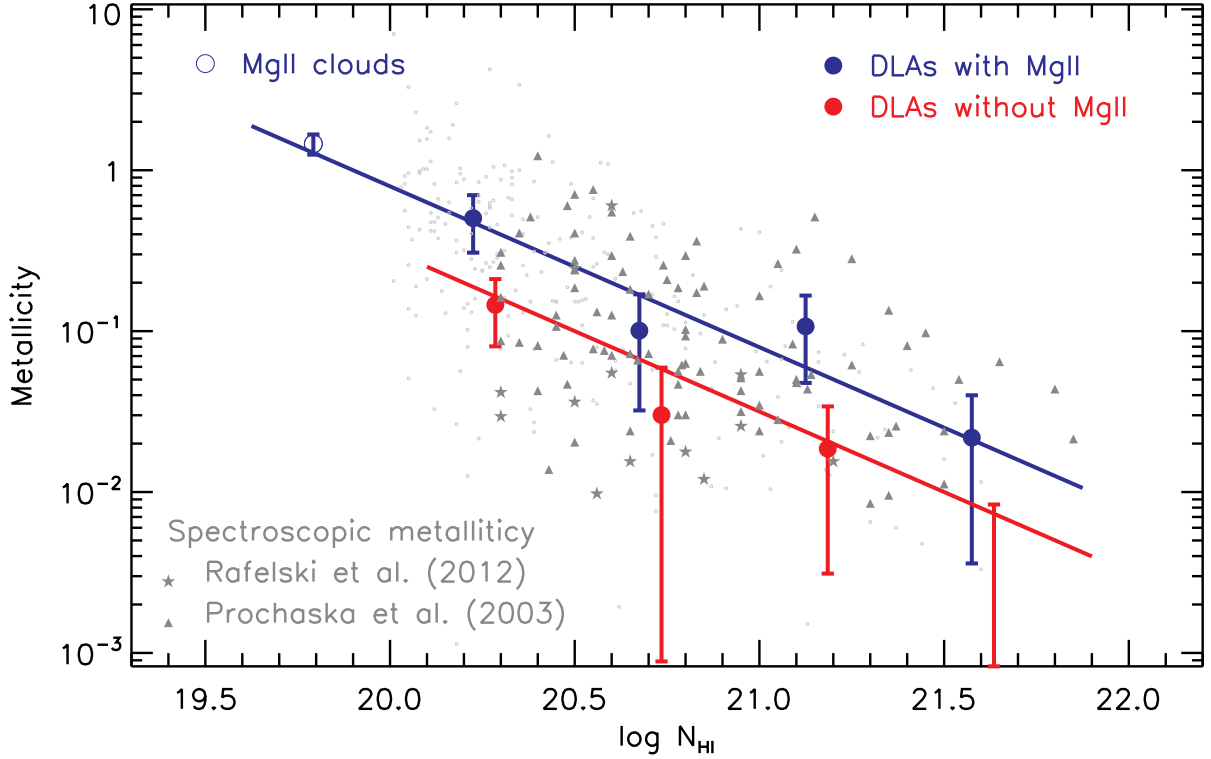


FIG. 4.— Median metallicity of the absorbers as a function of  $N_{\text{HI}}$  for absorbers with  $2.1 < z < 2.3$ . Solid blue circles are median metallicity for clouds showing the Mg II absorption with  $0.8\text{\AA} < W_0$ , solid red circles are that for clouds without MgII, both estimated from median reddening in  $g-i$  colour. The lines are fit with the slope fixed to  $Z \propto N_{\text{HI}}^{-1}$ . The open symbol at  $\log N_{\text{HI}} = 19.8$  is for MgII absorbers. Thin symbols show spectroscopic estimates for metallicity for DLA in  $2.1 < z < 2.3$ , taken from Prochaska et al. (2008) (diamonds) and Rafelski et al. (2012) (triangles). We also displayed individual measurements by small dots to show the extent of scatter: those with negative values are not shown.

us. This does not agree with the reddening we observed<sup>3</sup>, supporting the validity of the SMC type extinction law for DLAs. The MW type extinction, that should lead to very small reddening or blueing instead, is excluded.

With the SMC type extinction curve (Weingartner & Draine 2001), we have  $k(z_{\text{abs}} = 2.1) \simeq 3.0$  to  $k(z_{\text{abs}} = 2.3) \simeq 3.2$ . With equation (2) reddening measures the total amount of metals along the column, assuming that heavy elements condense to dust grains by a known fraction.

Figure 3 shows measured reddening  $\Delta(g-i)$  as a function of redshifts for absorbers  $2.1 < z_{\text{abs}} < 2.3$  for both raw measured value and value after hydrogen opacity subtracted. As expected from Figure 1 the dependence of  $\Delta(g-i)$  with hydrogen column density is weak and stays approximately at 0.05 mag. This corresponds to rest frame  $E(B-V) \approx 0.01$ .

Figure 4 shows metallicity of the damped Lyman  $\alpha$  clouds thus derived from the excess  $g-i$  colour caused by dust for the quasar flux passing through clouds, as a function of  $N_{\text{HI}}$  for absorbers at  $2.1 \leq z_{\text{abs}} \leq 2.3$ . Circles are median with the attached error bars denoting the variance. Plots are made separately for clouds showing Mg II features and those do not, both lie in parallel. We

use the median, but the use of the mean instead changes the plot little. We also plot with small thin dots the individual measurements for clouds. The scatter of the plot comes from variation of individual quasars, those caused by absorbers and photometric errors. These points are errors and individual points do not represent metallicity from each measurement; only the statistical average is a meaningful quantity. It should also be noted that individual measurements give both positive and negative values, as expected in Figure 1, and what are shown are only those that fall in the range of this figure.

The median is represented well by

$$Z \propto N_{\text{HI}}^{-1.0 \pm 0.2}, \quad (3)$$

for DLAs showing Mg II features, and

$$Z \propto N_{\text{HI}}^{-1.3 \pm 0.3}, \quad (4)$$

for DLAs without Mg II features, both indicating  $Z \propto 1/N$ . This means that the total metal abundance along the column hardly depends on the hydrogen column density of the cloud, as we noted in Figures 1 and 3 above. For this redshift range the contribution from Lyman alpha opacity, is small, as mentioned, which is anyway subtracted out (if not the power appears more like  $N_{\text{HI}}^{-0.8}$ ). We do not see any break beyond the error in this  $Z-N_{\text{HI}}$  correlation for the range  $N_{\text{HI}} = 10^{20.0} - 10^{21.8} \text{cm}^{-2}$ .

We also plot in this figure the spectroscopically es-

<sup>3</sup> We constantly observe reddening with DLAs in a wide range of redshift to  $z \approx 4$ . The reddening trend does not change as we work for a higher redshift. See text below.

timated metallicity for some DLA samples with triangles and diamonds (Rafelski et al. 2012; Prochaska & Wolfe 2009) restricted to the range  $2.1 \lesssim z_{\text{abs}} \lesssim 2.3$ . The overall agreement of metallicity from the dust abundance with spectroscopic metallicity, albeit statistical, reassures that our procedures do not commit substantial errors. In particular, this consistency holds with the SMC type extinction curve, but does not at all with the MW type extinction.

We note that the two curves, one with Mg II signature and the other without, obey parallel  $Z - N_{\text{HI}}^{-1}$  relations, meaning that all DLAs are dusty, irrespective of whether they show significant Mg II absorption or not. Those that show Mg II absorption have somewhat larger metallicity, approximately by a factor of 3. Whether a system shows Mg II absorption depends solely on the total Mg II abundance in the relevant column. When the total abundance of Mg II exceeds some threshold (roughly  $N_{\text{Mg}} \simeq 3 \times 10^{15} \text{cm}^{-1}$ ), the clouds are identified as Mg II absorbers with  $W_0 > 0.8\text{\AA}$ .

One data point added below our analysis threshold  $\log N_{\text{HI}} < 20$  refers to Mg II clouds in the  $W_0(\text{MgII}) > 0.8\text{\AA}$  sample in MF12. The H I column density is not directly measured for these absorbers. We infer it invoking the  $W_0 - N_{\text{H}}$  relation (Ménard & Chelouche 2009), taking account of the redshift dependence, to obtain  $\langle \log N_{\text{HI}} \rangle \approx 19.8$  (MF12), however, with a large scatter around the  $W_0 - N_{\text{H}}$  relation in mind. Metallicity of the Mg II clouds is about solar within a factor of two. We observe that Mg II absorption system is on the relation of metallicity hydrogen column density relation for DLA. There seems no discontinuity in this relation between Mg II and DLA: the total abundances of magnesium along the column in both absorbers are about the same.

This lack of DLA in the upper right plane (high  $Z$ , high  $N_{\text{HI}}$ ) has been noticed in the past in spectroscopic samples (e.g., Boissé et al. 1998; Péroux 2003; Khare et al. 2007). In particular, Meiring et al. (2009) obtained that  $[\text{Zn}/\text{H}] \sim 0.8 \log N_{\text{HI}}$ . This lack, however, has been ascribed to a selection effect against heavily reddened quasars, or to sometimes more complicated atomic effects (Krumholz et al. 2009). With only the spectroscopic sample one cannot conclude as to the cause.

This problem can be answered in our analysis, since we are measuring directly the extinction and we study when objects are obscured. We could observe quasars unless  $g-i$  reddening significantly exceeds unity. On the other hand, the bulk of the distribution of DLAs is below  $\Delta(g-i) = 0.3$  mag, as clear in Figure 1. The upper envelope of the distribution in Figure 4 corresponds roughly to  $\Delta(g-i) \approx 0.7$  for which quasars are still visible. This excess  $g-i$  is at a tail of the distribution and it is clear that an artificial cutoff due to visibility does not affect the global distribution of the  $\Delta(g-i)$ . Even if we would miss singularly, highly reddened quasars, they hardly affect our result. Therefore, the lack of high  $Z$ , high  $N_{\text{HI}}$  clouds in our analysis is not due to the selection effect from high obscuration. This lack of high  $Z$ , high  $N_{\text{HI}}$  clouds is intrinsic to the DLA.

We have extended a similar analysis to DLA clouds with higher redshifts  $z \leq 4$ , although we expect larger errors and systematics are not well controlled. Importantly,

however, we found that the reddening trend does not change with the amount consistent with what we observed for our  $2.1 < z < 2.3$  sample. The  $2175\text{\AA}$  hump goes off the  $i$  band for  $z > 2.8$ , and the MW extinction curve should lead to reddening. That we do not see any trend changing with redshift of DLA from  $z \approx 2.1$  to higher  $z$  is consistent with the smooth extinction curve of SMC.

#### 4. DUST IN DLA AND Mg II CLOUDS

We attempt to estimate the hydrogen and cosmic dust budget among quasar line absorbing clouds. We must bear in mind that there may be systematic effects arising from the treatment as to the selection of the absorption system. The numbers given below should be taken with reservations for the errors that may not be properly estimated. We consider, nevertheless, that it is worthwhile to envisage a global picture as to the distribution of hydrogen and dust in intergalactic objects.

With the SDSS DR9 catalogue Notredaeme et al. (2012) estimated H I mass density  $\Omega_{\text{HI}} \approx 1.0 \times 10^{-3}$  at  $z \simeq 2$ . We obtain with the uniform quasar sample of DR9  $\Omega_{\text{HI}} \simeq 8.6 \times 10^{-4}$ , using the DLA identification of Notredaeme et al. This value is two times larger than the HI abundance at  $z = 0$ ,  $\Omega_{\text{HI}} \simeq 4.2 \times 10^{-4}$  (Zwaan et al. 2003), meaning that the H I mass density further decreases towards  $z = 0$ . We remark, however, that Prochaska & Wolfe (2009)'s estimate at  $z \approx 2$ , is lower,  $4 \times 10^{-4}$ . DLAs identified by Prochaska & Wolfe are fewer. The difference seems to arise largely from the different treatment of the continuum around Lyman  $\alpha$  in the identification of DLA. We adopt here the more recent Notredaeme et al. catalogue without referring to this problem further.

The slope of the cloud abundance as a function of the hydrogen column density is a matter of argument (e.g., Prochaska et al. 2005; Péroux et al. 2003) below the DLA column density, *i.e.* around the Lyman limit system, LLS:  $10^{17.3} < N_{\text{HI}} < 10^{20.3}$ . Adopting the slope  $\alpha = -1.0$  of Prochaska et al. (2005) for this column density range, we extrapolate the DLA abundance to the LLS to obtain  $\Omega_{\text{HI}} \approx 2 - 4 \times 10^{-4}$ , which is half the DLA H I mass density.

For our DLA sample, we estimate the incidence of Mg II absorption to be approximately 10 %. The fraction of clouds that show Mg II absorption with  $W_0 > 0.8\text{\AA}$  is shown in Figure 5. It stays roughly at constant, at 10% independent of the hydrogen column density above  $10^{20} \text{cm}^{-2}$ .

To account for the total incidence of Mg II absorbers, however, we are led to guess that the fraction should go up to 40% in the LLS regime. Adding DLA that shows Mg II absorption, Mg II clouds amounts to  $\Omega_{\text{HI}}(\text{MgII}) \simeq 2.1 \times 10^{-4}$ , in our estimate based on the H I sample. This value is not inconsistent with our previous estimate based on the Mg II line selected sample,  $1.5 \times 10^{-4}$  (MF12), if errors from the sample selection is considered. Taking the fraction of Mg II clouds in DLA, we estimate the mass density of Mg II clouds in DLA as  $0.12 \times 8.6 \times 10^{-4} \simeq 1 \times 10^{-4}$ . Subtracting this from the the H I mass density in Mg II clouds, we estimate that the H I mass density in Mg II clouds in the LLS regime is  $\approx 1 \times 10^{-4}$ . Comparing this with  $\Omega_{\text{HI}}(\text{LLS})$  above, we infer that there may be

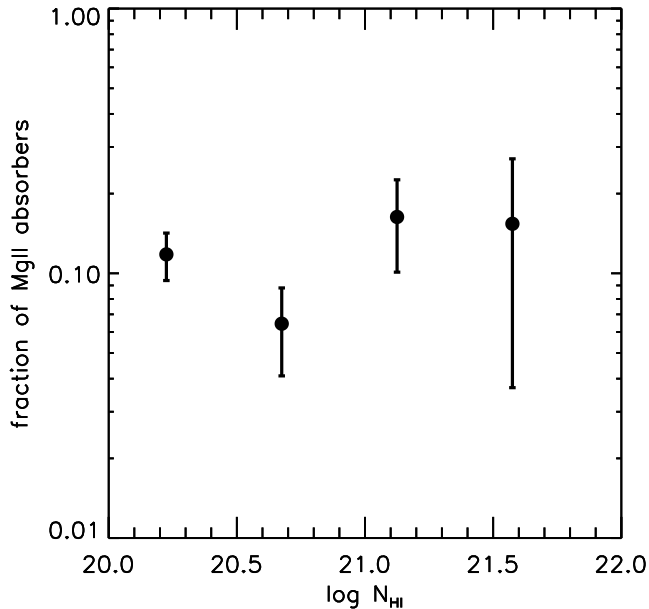


FIG. 5.— Fraction of clouds that show Mg II absorptions with  $W_0(\text{MgII}) > 0.8\text{\AA}$  as a function of the hydrogen column density.

more clouds (roughly up to 3 times more) in the LLS regime that do not show Mg II lines, *i.e.* are metal poor.

In MF12 we estimate that  $\Omega_{\text{dust}}(\text{MgII}) \simeq 2.3 \times 10^{-6}$ . For the DLA sample, we obtain  $\Omega_{\text{dust}}(\text{DLA}\&\text{MgII}) \simeq 1.6 \times 10^{-7}$ , which should be included in the MF12 estimate. More dust, however, is associated with non-Mg II DLAs, which is estimated to be  $\Omega_{\text{dust}}(\text{DLA}\&\text{nonMgII}) \simeq 5.0 \times 10^{-7}$ . Dust in DLA as a whole,  $\Omega_{\text{dust}}(\text{DLA}) \simeq 7 \times 10^{-7}$  is still 3 times less than that in Mg II clouds, namely it is only some modest addition to the global dust budget in absorption clouds.

We estimate dust in LLS showing Mg II absorption to be  $2.1 \times 10^{-6}$ . We are not able to estimate dust in non-Mg II absorbing LLS from our samples. It could bear an amount comparable to that in Mg II clouds with the LLS hydrogen density,  $\Omega_{\text{dust}}(\text{LLS, noMgII}) \sim 2 \times 10^{-6}$  if we assume 1/3 the metallicity of Mg II clouds, as we found for DLA. On the other hand, non Mg II LLS could be metal poor (hence dust poor) or dominantly pristine with negligible dust, as has been uncovered by Fumagalli et al. (2011) for their examples.

Adding all, we estimate the amount of dust in all intergalactic absorbers  $\Omega_{\text{dust}} \approx 3 - 5 \times 10^{-6}$ . This larger value agrees with what we infer from reddening of rays passing in the vicinity of galaxies (Ménard et al. 2010, hereinafter MSFR; Fukugita 2011). When dust in galaxies ( $4 \times 10^{-6}$ ) (Fukugita & Peebles 2004) is added, there seems to be, at least, no obvious missing dust in view of the present error, when compared with the amount that ought to be produced in the history of galaxy (Fukugita 2011). This consideration shows that dust observed is consistent with the amount that is produced in stars in galaxies ( $10 \times 10^{-6}$ ), allowing for a possibility of some amount (say  $\leq 20 - 30\%$ ) still missing, or destructed.

## 5. INTERPRETATION AND IMPLICATIONS

Low metallicity of DLAs indicates that they are primarily aggregates of pristine gas, rather than gas processed by stars, as with Mg II clouds. Metallicity of DLAs, however, is non vanishing. The notable feature is that metallicity is inversely proportional to the hydrogen column density.

We can think of two possibilities to enrich DLA with metals, star formation activity in DLA themselves and the contamination from outside via winds from other galaxies. For nearby galaxies it is established that star formation rate is proportional to a power of hydrogen column density, known as the Kennicutt (1998) law,  $N_{\text{H}}^{1.4}$  above the hydrogen column density threshold,  $N_{\text{H}} \approx (0.5 - 1) \times 10^{21} \text{ cm}^{-2}$ . Below this column density, the star formation efficiency drops sharply.

The Kennicutt law leads us to expect that the column density of star formation, hence the heavy element production and the dust production, when divided by  $N_{\text{H}}$ , is proportional to  $N_{\text{H}}^{+0.4}$  above some threshold. This is contrary to the trend in our analysis,  $N_{\text{H}}^{-1}$ . We do not detect any threshold in the metallicity versus hydrogen column density relation around  $N_{\text{H}} \approx (0.5 - 1) \times 10^{21} \text{ cm}^{-2}$ , which is known for the Kennicutt law. This leads us to conclude that the observed characteristics do not agree with the idea that dust is produced *in situ* star formation in DLA, at least, as far as the dominant part of dust is concerned, although it is known at low redshift that some DLAs are parts of galaxies of a variety of morphological types (e.g., Le Brun et al. 1997; Rao et al. 2003).

We argued that gas and dust in Mg II clouds are likely to be transported by stellar activity in nearby galaxies via galactic winds (MF12). This hypothesis may also apply to DLA. We expect that intergalactic objects may receive deposit from intergalactic gas at the same amount per unit area of the surface. This means that the average metallicity should be inversely proportional to the column density, in agreement with what is observed here. We expect that galactic winds are ubiquitous throughout the universe. In our earlier publication (MSFR) we have shown that the abundance ratio of dust to dark matter stays approximately constant to a scale larger than a few Mpc away from galaxies. Knowing that the mean dark matter distribution obeys a power law, roughly as  $r^{-2.4}$  to far beyond the virial radius of the galaxy (Masaki et al. 2012), we infer that dust also follows a similar power law without cutoff to a few Mpc scale.

The total global amount of dust in galaxies and absorbers is consistent with what is ought to be produced in star formation in galaxies. This implies that effective lifetime of dust, including its possible regeneration, is of the order of the age of the universe. It is somewhat puzzling to note that a clear discontinuity is not observed between Mg II absorbers and DLAs in their metallicity distributions, while the dust to gas ratio in Mg II clouds implies that they are predominantly of galactic activity origins: they should not be diluted much with pristine gas.

The amount of dust deposited to each cloud should vary: in particular, it would depend on the distance to and on dust producing activity of nearby galaxies. It is interesting to look at the analysis of Krogager et al. (2012), who considered metallicity and  $N_{\text{H}}$  of the DLAs as a function of the distance to their nearest galaxies.



Their metallicity plot scatters too wildly to give a clear interpretation. If their data are re-plotted as  $Z$  times  $N_{\text{HI}}$  (total metal abundance deposited per unit surface area) versus the distance to galaxies, however, the plot indicates that  $ZN_{\text{HI}}$  (total amount of metals) anticorrelates with the distance to the nearby galaxy, although the sample is too small and the trend suffers from a large scatter to draw a definitive conclusion.

## 6. CONCLUSIONS

We have studied metallicity of DLA using dust therein as an indicator. The advantage is that the dust abundance can be estimated passively from the extinction of light passing through the object, provided that care is made to measure a small value of reddening. To keep the accuracy controlled we choose some narrow redshift ranges both for absorbers and quasars. Using the fact that 30% of heavy elements condense into dust grains, metallicity can be estimated from reddening in broad band photometry. This requires averaging over a large data set and well-controlled photometry that does not suffer from arbitrary errors. The advantage is that the estimate of metallicity, using only passive measurements, does not use the temperature, or does not depend on the environment such as the radiation field. Our central conclusion is that average metallicity is inversely proportional to the column density of the DLA, as  $Z \sim N_{\text{HI}}^{-1}$ , or in other words, the metal column density stays constant independent of the hydrogen column density.

We argued that *in situ* star formation should lead to  $Z \sim N_{\text{HI}}^{+0.4}$ , which contrasts to the observation of the inverse correlation. We have not observed any threshold in the hydrogen column density that is known for the Kennicutt law of star formation (Kennicutt 1998; see also Wyder et al. 2009). These aspects lead us to conclude that it is unlikely to ascribe the origin of the bulk of dust in DLA to *in situ* star formation. We argued as the alternative that dust in DLA is the deposit from intergalactic space through stellar activity around the cloud, with which we expect, on average, the same amount of dust deposited per surface area of intergalactic clouds irrespective of the column density. It then follows that

$Z \sim N_{\text{HI}}^{-1}$ . We discussed that this view does not bring a problem into the dust budget consideration.

About 10% of DLAs show Mg II absorption features at  $z \sim 2$ . DLAs that do not show strong Mg II absorption features harbour 1/3 the amount of dust compared with those that show strong Mg II absorption. As a result, dust in DLAs as a whole resides more in those that do not show Mg II absorption features. The global amount of dust in DLAs, however, is yet 1/3 the amount in Mg II clouds, which are mostly at lower, LLS column densities.

A corollary result from our study is that dust in DLA shows reddening consistent with the SMC type extinction curve. For the redshift we chose ( $z \approx 2.2$ ) the Milky Way type extinction would lead to no colour excess or even blueing in  $g - i$  colour in the presence of dust due to the 2175Å feature. We detected reddening when DLA is present in the foreground, and metallicity derived using the SMC type extinction curve agrees statistically with spectroscopic estimates. This rules out the Milky Way type extinction for the DLA.

DLAs seem to be aggregates of primarily pristine gas with small amount of deposits from the galaxy activity in their vicinity. On the other hand, Mg II clouds are consistent with secondary products of galaxies diluted little with pristine gas. However, there seems to be no clear dichotomy in the metallicity hydrogen column density relation between the two populations. Mg II clouds should thoroughly be contaminated, or even dominated by galactic wind, if they are of the primordial origin. There seems to be a significant population of hydrogen clouds with the hydrogen column density comparable to Mg II clouds but do not show Mg II lines: they seem to be a population similar to DLAs at a lower column density extinction. How Mg II clouds formed remains as an interesting problem.

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## REFERENCES

- Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2012, ApJS, 203, 21 (DR9)
- Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
- Boissé, P., Le Brun, V., Bergeron, J., & Deharveng, J.-M. 1998, A&A, 333, 841
- Frank, S., & Péroux, C. 2010, MNRAS, 406, 2235
- Fukugita, M. 2011, arXiv:1103.4191
- Fukugita M., & Peebles P. J. E., 2004, ApJ, 616, 643
- Fumagalli, M., O’Meara, J. M., & Prochaska, J. X. 2011, Science, 334, 1245
- Heckman, T. M., Lehnert, M. D., Strickland, D. K., & Armus, L. 2000, ApJS, 129, 493
- Kennicutt, R. C., Jr. 1998, ApJ, 498, 541
- Khare, P., Kulkarni, V. P., Péroux, C., et al. 2007, A&A, 464, 487
- Khare, P., Vanden Berk, D., York, D. G., Lundgren, B., & Kulkarni, V. P. 2011, arXiv:1109.4225
- Krogager, J.-K., Fynbo, J. P. U., Møller, P., et al. 2012, MNRAS, 424, L1
- Krumholz, M. R., Ellison, S. L., Prochaska, J. X., & Tumlinson, J. 2009, ApJ, 701, L12
- Le Brun, V., Bergeron, J., Boissé, P., & Deharveng, J. M. 1997, A&A, 321, 733
- Masaki, S., Fukugita, M., & Yoshida, N. 2012, ApJ, 746, 38
- Meiring, J. D., Lauroesch, J. T., Kulkarni, V. P., et al. 2009, MNRAS, 397, 2037
- Ménard, B., & Chelouche, D. 2009, MNRAS, 393, 808
- Ménard, B., & Fukugita, M. 2012, ApJ, 754, 116 (MF12)
- Ménard, B., Nestor, D., Turnshek, D., et al. 2008, MNRAS, 385, 1053
- Ménard B., Scranton R., Fukugita M., Richards G., 2010, MNRAS, 405, 1025 (MSFR)
- Nestor, D. B., Turnshek, D. A., & Rao, S. M. 2005, ApJ, 628, 637
- Noterdaeme, P., Petitjean, P., Carithers, W. C., et al. 2012, A&A, 547, L1
- Pâris, I., Petitjean, P., Aubourg, É., et al. 2012, A&A, 548, A66
- Péroux, C., Dessauges-Zavadsky, M., D’Odorico, S., Kim, T.-S., & McMahon, R. G. 2003, MNRAS, 345, 480
- Prochaska, J. X., Gawiser, E., Wolfe, A. M., Castro, S., & Djorgovski, S. G. 2003, ApJ, 595, L9
- Prochaska, J. X., Herbert-Fort, S., & Wolfe, A. M. 2005, ApJ, 635, 123
- Prochaska, J. X., & Wolfe, A. M. 2009, ApJ, 696, 1543
- Rafelski, M., Wolfe, A. M., Prochaska, J. X., Neeleman, M., & Mendez, A. J. 2012, ApJ, 755, 89

- Rao, S. M., Nestor, D. B., Turnshek, D. A., et al. 2003, *ApJ*, 595, 94
- Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, *ARA&A*, 43, 769
- Vladilo, G., Prochaska, J. X., & Wolfe, A. M. 2008, *A&A*, 478, 701
- Weiner, B. J., Coil, A. L., Prochaska, J. X., et al. 2009, *ApJ*, 692, 187
- Weingartner, J. C., & Draine, B. T. 2001, *ApJ*, 548, 296
- Wyder, T. K., Martin, D. C., Barlow, T. A., et al. 2009, *ApJ*, 696, 1834
- York, D. G., Khare, P., Vanden Berk, D., et al. 2006, *MNRAS*, 367, 945
- Zhu, G., & Ménard, B. 2013, *ApJ*, 770, 130
- Zwaan, M. A., Staveley-Smith, L., Koribalski, B. S., et al. 2003, *AJ*, 125, 2842